Final Report
on the project

VUV Radiation and Breakdown

AFOSR FA9550-08-1-0141

For the period March 1, 2008 to January 31, 2011

To:

AFOSR/NE John Luginsland
801 N. Randolph Street, Rm 732
Arlington, VA 22203

From:

Center for Pulsed Power and Power Electronics
Departments of Electrical and Computer Engineering and Physics
Texas Tech University
Lubbock, Texas 79409-3102

February 28, 2011

Principal Investigator
Andreas A. Neuber
Andreas.Neuber@ttu.edu
806-742-1250

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
28 FEB 2011	**FINAL REPORT**	**01-03-2008 to 31-01-2011**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
VUV Radiation and Breakdown	**FA9550-08-1-0141**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
ANDREAS NEUBER	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Texas Tech University,Departments of Electrical and Computer Engineering and Physics,Lubbock,TX,79409-3102	**; AFRL-OSR-VA-TR-11-038**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR, 875 N RANDOLPH ST, ARLINGTON, VA, 22203	11. SPONSOR/MONITOR'S REPORT NUMBER(S) **AFRL-OSR-VA-TR-11-038**

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Two experimental setups have been used in this work on the effects of vacuum ultraviolet light on surface breakdown. The first experimental setup was designed so that VUV emission from an excited surface flashover event is focused onto the entrance slit of a vacuum spectrograph, with the spark simultaneously being imaged by a fast shutter ICCD on the atmospheric side. The dielectric surface was an MgF2 window and an MgF2 lens was used to focus the light on the spectrometer entrance slit. The second experimental setup used mirrors in place of the MgF2 lens thus increasing the light below 130 nm entering the spectrometer.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**17**	

EXECUTIVE SUMMARY

This work resulted in two MS degrees in Electrical Engineering. The references to the theses are listed below. A brief summary of the results is given here with the author's name attached.

Garrett Rogers

An experimental setup used to study pulsed dielectric surface flashover in various gases at atmospheric pressure has returned results on streamer formation. Images of streamer formation in oxygen, air, and nitrogen with high temporal resolution have been studied and analyzed. Streamer velocity and the charge in the streamer have been found as well as some information on streamer formation. A short current spike occurring prior to breakdown of the gap has been studied and it has been shown that this occurs when the primary streamer reaches the cathode. In oxygen, it is seen that the current drops down to the levels seen prior to the spike, but, in nitrogen and air, this current spike serves as a sort of current amplification mechanism as the current continues rising without drop before the gap breaks down. It has also been revealed that more VUV is emitted from the gap prior to breakdown with nitrogen and air present than in oxygen.

Breakdown voltage has been observed in each gas, and it has been found that oxygen has the highest breakdown voltage followed by nitrogen and then air. Since air is composed of mostly oxygen and nitrogen, it would seem that the breakdown voltage of air should lie between oxygen and nitrogen. It has been shown possible that radiation emitted by nitrogen is absorbed by oxygen which would explain air having the lowest breakdown voltage of the three gases.

George Laity

The overall objective of this experiment was to observe VUV emission from pulsed atmospheric discharges, with emphasis on time resolved measurements which show the impact of VUV radiation on streamer propagation. A significant amount of VUV emission was observed from excited surface flashover events, and most of this activity was recorded during the nanoseconds leading into voltage collapse with limited VUV production for the remaining microseconds. The best fit of Boltzmann electronic temperature for the recorded emission profile in the flat region of limited absorption correction was 10 eV, which was calculated using a spectral simulation software package developed at Texas Tech. Virtually all emission lines between 120 and 180 nm observed from flashover correspond to excitations of atomic nitrogen and oxygen.

It was shown from corresponding electrical diagnostics that the VUV emission is tied to fluctuations of voltage from proposed streamer events which successfully bridge the flashover gap. Detailed streamer imaging from the atmospheric side agrees with the electrical and VUV emission diagnostics, in the sense that small current spikes coupled with voltage drops could be caused from VUV induced streamer activity. It is possible to simultaneously record VUV emission, electrical waveforms, and high resolution optical images with nanosecond timescales.

The results of the electrostatic field simulations support the observed streamer behavior for a number of field geometries. It was concluded from these simulations that the field enhancement factor is maximized for the case when the cathode is hard

grounded to the steel structure of the input window flange, and the resulting electric field at the triple point produces the most luminous cathode directed streamer activity in the study. Hard grounding of the anode produced a negative high voltage geometry, which produced slower and more diffuse anode directed streamers which agree with theory Because significant atomic excitations are observed from atmospheric discharges, it can be assumed that some mechanism exists which dissociates molecular gases during the breakdown process. Furthermore, the ionization energies for atmospheric gases are on the order of 12 - 15 eV, which correspond to wavelengths in the range of 70 – 90 nm. A next generation VUV emission setup is currently in the planning stage which extends the sensitivity of the diagnostics into this range.

PERSONNEL

Faculty members

Andreas A. Neuber, PI
James Dickens, Co-PI
Herman Krompholz

Visitors

Klaus Frank, retired Professor from University of Erlangen-Nürnberg
Thomas Schramm, graduate student from University of Erlangen-Nürnberg

Research Associates

John Krile, Research Associate
Lynn L. Hatfield, Senior Research Associate

Graduate Students

George Russell Laity
Andrew S. Fierro
Truman G. Rogers

Undergraduate Student Assistants

Jacob Stephens
Gary Stinnett
Joseph VanDeventer

High School Student

J. B. Moss

JOURNAL ARTICLES PUBLISHED

[J1] G. Laity, A. Fierro, L. Hatfield, J. Dickens, A. Neuber, "Spatially Resolved Vacuum UV Spectral Imaging of Pulsed Atmospheric Flashover," *IEEE Transactions on Plasma Science*, (submitted for special issue December 2010).

[J2] G. Laity, A. Fierro, A. Neuber, J. Dickens, L. Hatfield, "Phenomenology of

Streamer Propagation during Pulsed Dielectric Surface Flashover," *IEEE Transactions on Dielectrics and Electrical Insulation*, (accepted for publication January 2011).

[J3] G. Laity, A. Neuber, G. Rogers, K. Frank, "System for Time Resolved Spectral Studies of Pulsed Atmospheric Discharges in the Visible to Vacuum Ultraviolet Range," *Review of Scientific Instruments* 81, 083103, (2010).

[J4] G. Rogers, A. Neuber, K. Frank, G. Laity, J. Dickens, "VUV Emission and Streamer Formation in Dielectric Surface Flashover at Atmospheric Pressure," *IEEE Transactions on Plasma Science* 38, 2764, (2010).

CONFERENCE PAPERS PRESENTED

[C1] G. Laity, A. Neuber, A. Fierro, J. Dickens, L. Hatfield, "Nanosecond-Scale Spectroscopy of Vacuum Ultraviolet Emission from Pulsed Atmospheric Discharges," *18th IEEE International Pulsed Power Conference*, June 19th – 23rd, Chicago, IL, (to be presented 2011).

[C2] A. Fierro, G. Laity, L. Hatfield, J. Dickens, A. Neuber, "Advanced Imaging of Pulsed Atmospheric Surface Flashover," *18th IEEE International Pulsed Power Conference*, June 19th – 23rd, Chicago, IL, (to be presented 2011).

[C3] K. Frank, G. Laity, A. Neuber, G. Rogers, L. Hatfield, J. Dickens, M. Kristiansen, A. Fierro, "Time-Resolved Spectral Investigations of Pulsed Atmospheric Dielectric Surface Flashover Discharges," *63rd Gaseous Electronics Conference*, October 4th – 8th, Paris, France, (2010).

[C4] G. Laity, H. Krompholz, A. Neuber, L. Hatfield, K. Frank, A. Fierro, J. Dickens, M. Kristiansen, "Pulsed Atmospheric Breakdown," *AFOSR Counter High Power Microwaves Meeting*, July 29th – 30th, Albuquerque, NM, (2010).

[C5] A. Neuber, H. Krompholz, J. Dickens, J. Krile, J. Foster, S. Beeson, M. Thomas, G. Laity, A. Fierro, "Pulsed Breakdown and Flashover at Atmospheric Pressure," *AFOSR Counter High Power Microwaves Meeting*, July 29th – 30th, Albuquerque, NM, (2010).

[C6] G. Laity, A. Neuber, G. Rogers, K. Frank, L. Hatfield, J. Dickens, "Spectral Analysis of Vacuum Ultraviolet Emission from Pulsed Atmospheric Discharges," *37th IEEE International Conference on Plasma Science*, June 20th – 24th, Norfolk, VA, (2010).

[C7] G. Rogers, A. Neuber, L. Hatfield, G. Laity, K. Frank, J. Dickens,

"Atmospheric Flashover in a Symmetric Electric Field Geometry," *2010 IEEE International Power Modulator and High Voltage Conference*, May 23rd – 27th, Atlanta, GA, (2010).

[C8] K. Frank, J. Dickens, L. Hatfield, M. Kristiansen, G. Laity, A. Neuber, G. Rogers, "First Results of Streamer Formation During Dielectric Surface Flashover at Atmospheric Conditions," *DPG Spring Meeting of the Atoms, Molecules, Optics, and Plasmas Section*, March 8th – 12th, Hannover, Germany, (2010).

[C9] G. Laity, K. Frank, G. Rogers, A. Neuber, J. Dickens, J.B. Moss, "Initial Results of Time-Resolved VUV Spectroscopy of Pulsed Dielectric Surface Flashover in Atmosphere," *51st Annual Meeting of the APS Division of Plasma Physics*, November 2nd – 6th, Atlanta, GA, (2009).

[C10] G. Rogers, A. Neuber, G. Laity, T. Schramm, J. Dickens, K. Frank, "VUV Emission from Dielectric Surface Flashover at Atmospheric Pressure," *Proceedings of the 17th IEEE International Pulsed Power Conference*, June 29th – July 2nd, Washington, DC, pp. 855 – 859, (2009).

[C11] G. Laity, K. Frank, G. Rogers, M. Kristiansen, J. Dickens, A. Neuber, T. Schramm, "Vacuum Ultraviolet Spectroscopy of Dielectric Surface Flashover at Atmospheric Pressure," *36th IEEE International Conference on Plasma Science*, May 31st – June 5th, San Diego, CA, (2009).

MS THESIS IN ELECTRICAL ENGINEERING

[R1] G. Laity, "Vacuum Ultraviolet Spectroscopy of Dielectric Surface Flashover in Atmosphere: A Thesis in Electrical Engineering," *Texas Tech University ETD Database*, (2010).

[R2] Rogers, Garrett, "A Study of Pulsed Dielectric Surface Flashover at Atmospheric Pressure": A Thesis in Electrical Engineering," *Texas Tech University ETD Database*, (2010).

INTRODUCTION

Two experimental setups have been used in this work on the effects of vacuum ultraviolet light on surface breakdown. The first experimental setup was designed so that VUV emission from an excited surface flashover event is focused onto the entrance slit of a vacuum spectrograph, with the spark simultaneously being imaged by a fast shutter ICCD on the atmospheric side. The dielectric surface was an MgF_2 window and an MgF_2 lens was used to focus the light on the spectrometer entrance slit. The second experimental setup used mirrors in place of the MgF_2 lens thus increasing the light below 130 nm entering the spectrometer.

FIRST EXPERIMENTAL SETUP

The ICCD used for imaging is the DH734 series camera from Andor™ Technology minimum gate time of 2 ns focused by a Nikon 25 mm lens. Sharpened stainless steel electrodes estimated tip radius of 200 m are attached to springs which press the electrodes down onto an surface so they are a distance of 8 mm apart see Figure 1. Magnesium fluoride MgF_2 was chosen as the window dielectric since it is VUV transparent down to around 117 nm.

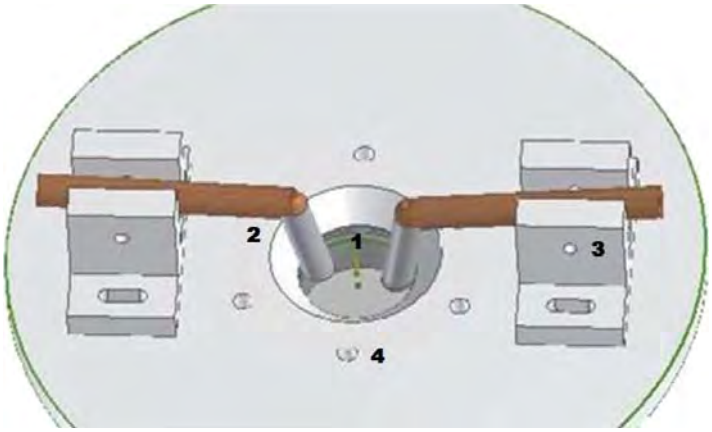

Figure 1. Flashover apparatus used for pulsed studies: 1- MgF_2 window surface, 2 -sharpened electrodes, 3-spring electrode holders, and 4-flange mounting holes.

The entire flashover gap is contained in a Lexan chamber, which enables flashover testing in diverse gases and gas mixtures at atmospheric pressure. Utilizing a triggerable solid-state pulser, a high voltage pulse is applied to the flashover electrodes. The circuit basically consists of a charged capacitor which is thyristor switched into a pulse transformer see Figure 2.

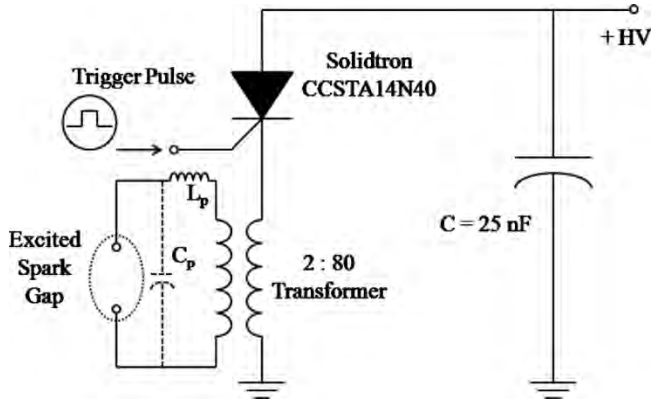

Figure 2. High voltage excitation circuit, with 2:80 transformer step-up ratio. *Lp* and *Cp* are parasitic circuit elements.

This pulser produces adjustable voltage amplitude of up to 50 kV across the flashover gap and a pulse rise-time of 100 ns with 500 ns pulse-width. VUV emission is observed when the gap is allowed to flash over while overvoltaged, with a peak voltage of typically 22 kV and a circuit limited current of 40 A with low temporal jitter. High-speed voltage and current diagnostics in conjunction with ICCD gate diagnostics allow for reconstructive analysis of the exact timing of an image with respect to the breakdown point.

VUV emission from the surface flashover event transitions from atmosphere into vacuum (10−7 torr) through the MgF_2 window and propagates toward the spectrograph entrance slit see Figure 3. In order to allow for maximum intensity in the spectrograph, the VUV light is focused by an MgF_2 lens directly onto the adjustable spectrograph entrance slit. Since magnesium fluoride has a strongly varying index of refraction below 180 nm, the light path must be shortened or lengthened based on the target wavelength interval for a particular measurement. The exact length specifications for the light path were determined using OPTICAL RAY TRACER©, an open source software package available online. The calculated dimensions of the optical apparatus are given below in Table 1.

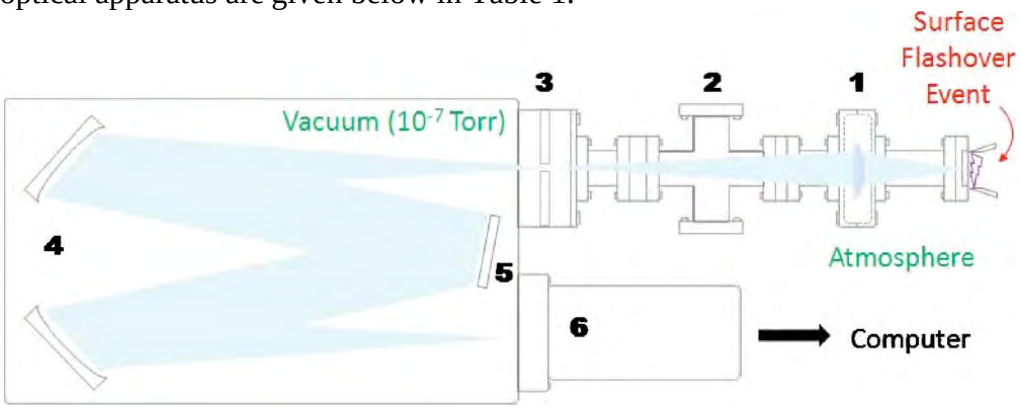

Figure 3. Light path and spectrograph used for pulsed spectral analysis: 1 MgF_2 lens compartment, 2 vacuum hook-ups and diagnostics, 3 spectrograph adjustable entrance slit, 4 coated spectrograph mirrors, 5 diffraction grating, and 6 exit slit and ICCD/PMT diagnostics.

Table 1. Optical system parameters.

Parameter	Value
Lens Focal Length (*f*)	89.4 mm
Optimized Wavelength (λ)	130 nm
Spectrograph Focal Length	500 mm
Spectrograph F - Number	8.7
Object – Lens Distance (x_o)	120 mm
Lens – Image Distance (x_i)	300 mm
Grating has 1200 lines/mm	17 Å/mm disp.

Either a VUV sensitive photomultiplier, (Hamamatsu R8486, 20% quantum efficiency below 200 nm), or the VUV sensitive ICCD camera (DH740 series camera from Andor™, 13% quantum efficiency with a minimum 2 ns gate) is mounted to the exit plane of the spectrograph. These both use MgF_2 windows for VUV transmission.

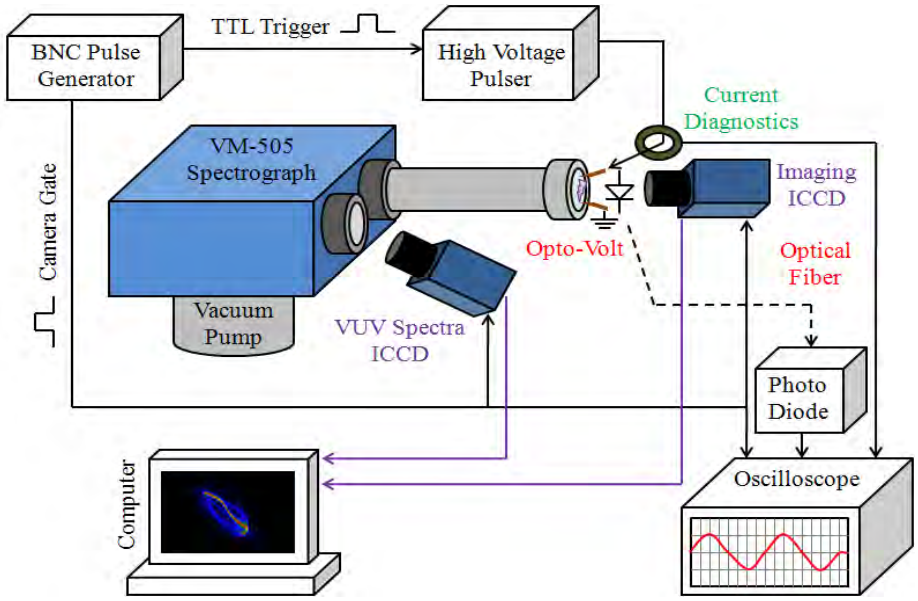

Figure 4. Overview of relevant diagnostics (optical and electrical) used in this study.

The current and voltage sensors were calibrated and were used to determine timing of the cameras with respect to the spark formation.

EXPERIMENTAL RESULTS FROM SETUP ONE

Typical voltage and current waveforms recorded during a flashover event in air are shown in Figure 5. The voltage rises across the flashover electrodes until roughly 25 ns before breakdown, when voltage fluctuations set in and the current begins to slowly rise. This period before full breakdown corresponds to the fast streamer phase, where photoionization is believed to play a major role. The PMT intensity shown in Figure 6 for 149.5 nm (which corresponds to atomic nitrogen emission) rapidly increases in the few nanoseconds before full spark breakdown.

Utilizing the ICCD output data it was possible to integrate the VUV emission during the full duration of the flashover event (see Figure 7, ICCD camera gated for 2 μs). As indicated, the prominent emission lines are identified as being emitted from atomic oxygen and nitrogen between 120 and 180 nm. The intensity of the measured VUV emission drops rapidly below 135 nm, which is attributed primarily to the falling transmission of MgF_2 down to its cutoff wavelength of 117 nm.

It should be noted that the most significant VUV activity in pulsed atmospheric discharges is observed during the initial fast stage of streamer propagation. This was confirmed by measuring the intensity of an atomic nitrogen emission line at 141.2 nm

wavelength in 100 ns intervals during the discharge period (see Figure 8). Maximum VUV emission occurs during the initial stage of discharge (as confirmed by the PMT measurements). Emission of VUV rapidly declines after full conduction occurs, with small resurgence at 200 and 600 ns. This resurgence is caused by the undamped current in the flashover circuit switching polarity with a half wave period of around 400 ns. There is obviously very limited VUV production for the remaining microseconds of the discharge where the current is still high, but the voltage has collapsed.

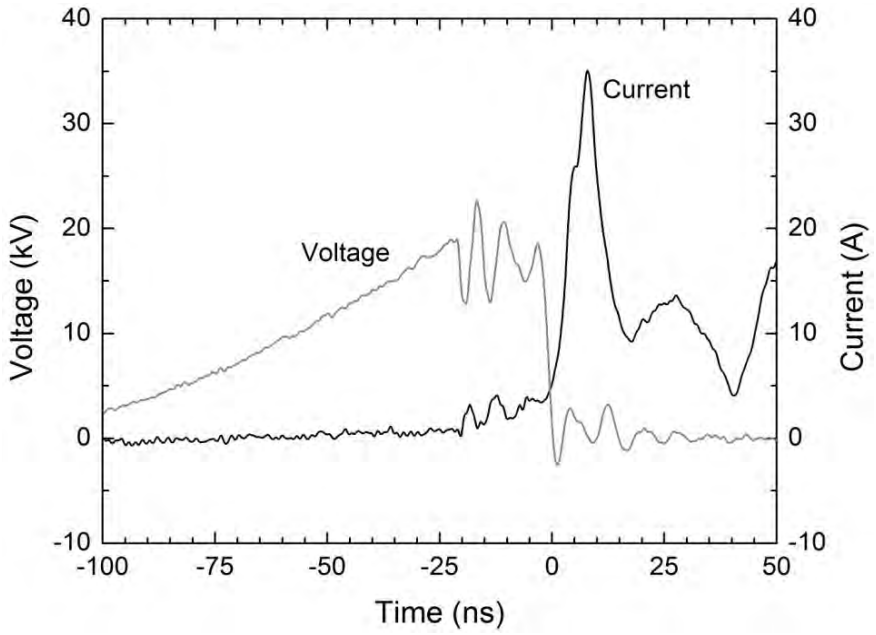

Figure 5: Typical current and voltage waveforms during triggered surface flashover.

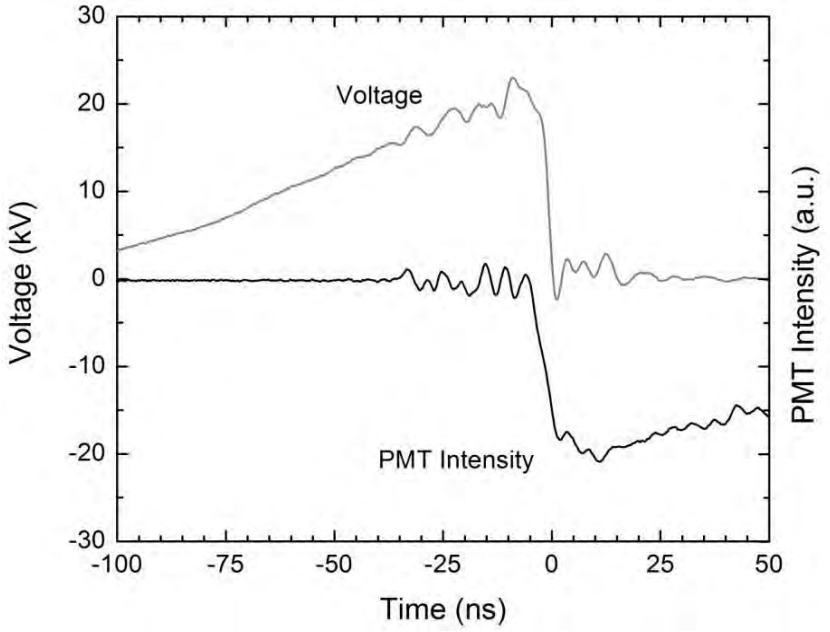

Figure 6: Typical voltage and PMT intensity waveforms.

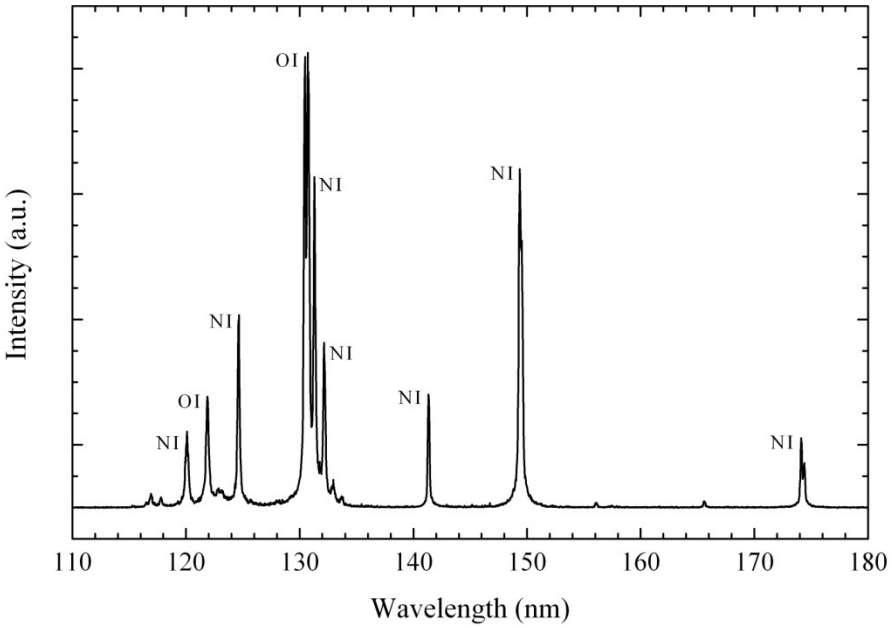

Figure 7: Typical VUV emission from surface flashover in atmospheric pressure air measured with the ICCD camera using a 2 μs gate time.

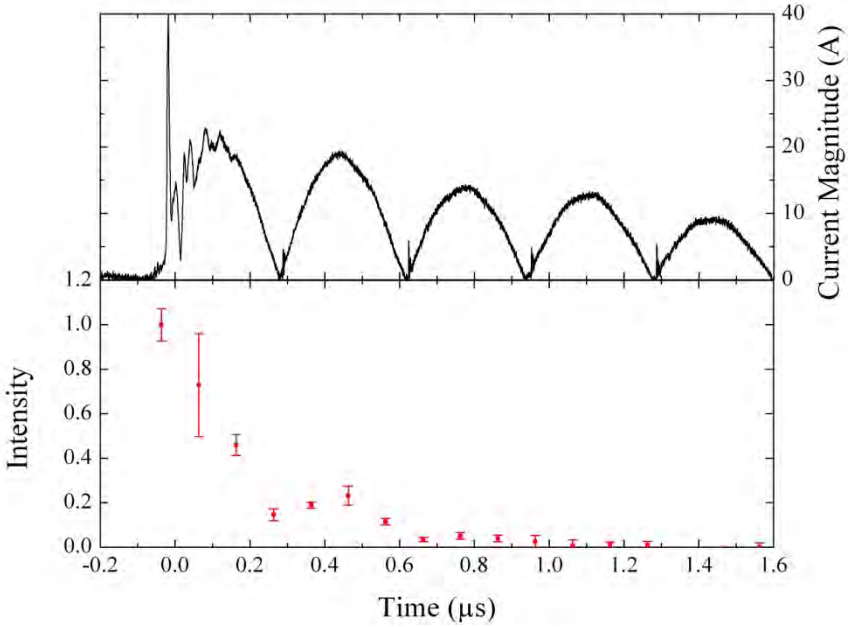

Figure 8: Time resolved intensity of emission (red squares) from the 141.2 nm line of nitrogen with a sample size of 5 for each 100 ns wide bin, and the corresponding current during breakdown (black).

This ICCD recording of VUV intensity in gated 100 ns intervals was repeated for a number of nitrogen emission lines in the VUV range (131.2, 131.9, 141.2, 149.3, 149.5 nm); and all produced a similar result.

Images of the flashover event were taken to visualize streamer propagation using the ICCD camera on the atmospheric side, with temporal resolution on the order of

nanoseconds, see Figure 9. The ICCD gate trigger in and the electrical diagnostics enable exact reconstruction of image timing. In the time up to 60 ns before breakdown the electrodes become very luminous, where the high field region accelerates electrons and leads to collisional excitations causing early photon emission. These photons travel away from the anode and can cause excitations and ionizations of the gas molecules in the gap, where the regions of highest activity are coupled with luminous streamer heads. This is confirmed by some initial activity of streamers showing they propagate away from the top anode towards the bottom cathode during the time before 40 ns. These streamers are also attracted to the outside steel flange which houses the MgF_2 window surface.

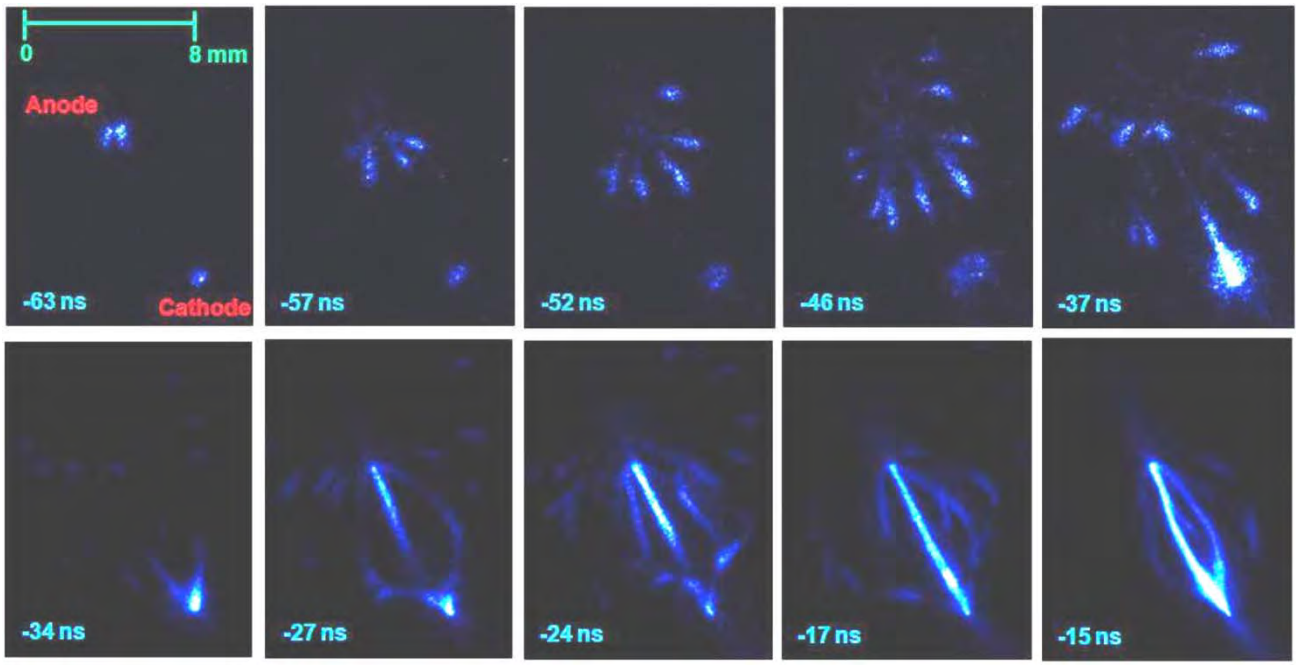

Figure 9: Image sequence of flashover events in high purity nitrogen atmosphere with short 3 ns gate time. The first frame shows the positions of the anode and cathode. Each frame is timed by how long it is before full breakdown determined by collapse of the voltage as in Figure 6.

The estimated propagation velocity of these early streamers with onset at about -63 ns in Figure 9 is around $4x10^7$ cm/s, which is on the order of what others have observed. Around 40 ns before breakdown the streamers (VUV photon driven ionization) connect with the cathode and secondary processes begin to fill the gap. At this point the recorded PMT intensity begins to experience significant fluctuations indicating VUV emission during this period, cf. Figure 8. The electrons which were initially produced from volume photoionization and possibly photoemission from the surface during the early stage have now already moved away, and only positive ion space charge remains. It appears that the first cathode directed streamer (all recorded flashovers originated from the anode) is insufficient to produce a fully conducting channel (cf. Figure 9, at t = -37 ns). While the pulse voltage is still increasing at ~200 V/ns, second generation cathode directed streamers cause the visible fluctuation in the current waveform at early times, cf. frame 7 with roughly three generations or frame 8 with more than four generations. Eventually a

fully conducting channel is established and main current starts to flow with a comparably sharp rise time. The only energy available for this sharp current rise is stored in the parasitic capacitance of the setup, C_p, estimated to be of the order of 10 pF, charged to the flashover voltage. Hence, the initial current spike is limited to a few 10s of ampere and a duration of about 10 ns. More current starts flowing after the initial current spike due to the main 25 nF capacitor pushing current through the pulse transformer and discharging through the flashover gap. The basic shape of the breakdown channel remains unchanged for times larger than -15 ns; rather, the intensity of the spark's self-luminosity is increasing significantly.

Note that the streamer images in Figure 9 are taken from successive shots, as the ICCD camera is only capable of single shot imaging. Hence, a direct comparison of the streamer images with the current waveforms needs to be done with caution. Only the small shot to shot fluctuations of the semiconductor switched high voltage pulser make a comparison a possibility at all.

SETUP TWO

The first equipment setup used an MgF_2 lens to focus the light from the breakdown event onto the spectrometer slit. The index of refraction and the transmission efficiency of the lens begins to change with wavelength below about 130 nm. This leads to chromatic aberration and smaller signal amplitude at short wavelengths as can be seen in Figure 7. The second setup uses off axis parabolic mirrors in place of the lens. The mirrors were coated with a proprietary, high reflectance coating for use in the VUV.

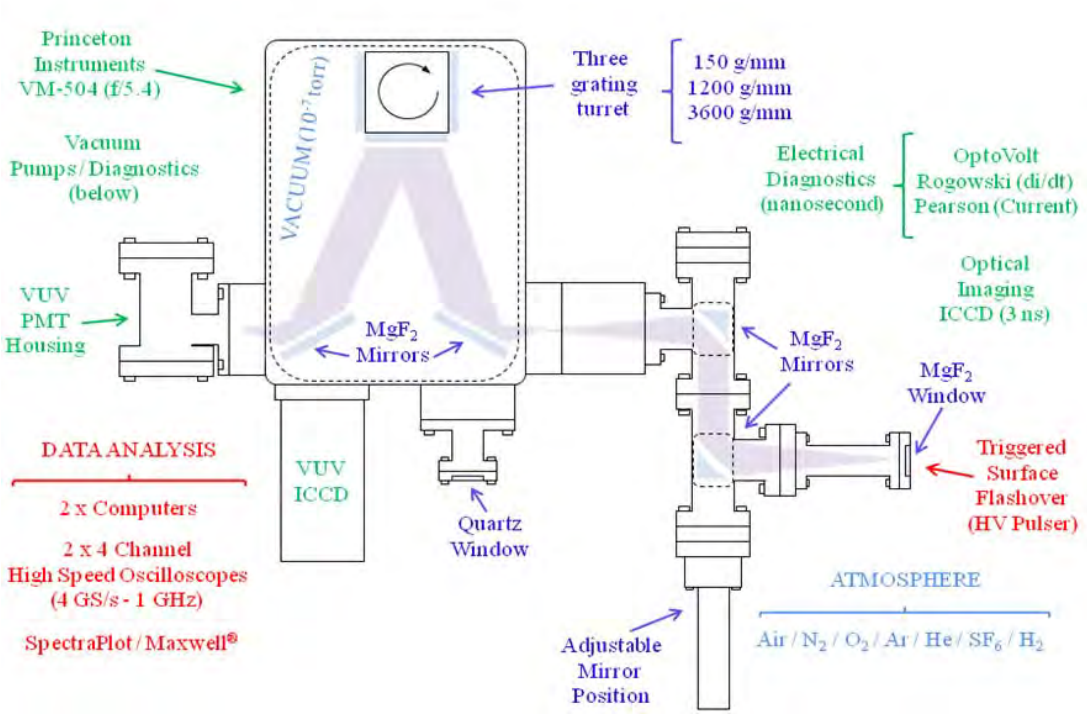

Figure 10: Second setup showing the new spectrometer with the off-axis parabolic mirrors.

The calibration of the spectrometer and the efficiency of the system were checked using a deuterium lamp (Hamamatsu L7292) which was mounted so that the MgF_2 window of the lamp was inside the vacuum system. Figure 11 shows excellent comparison with the published standard deuterium spectrum.

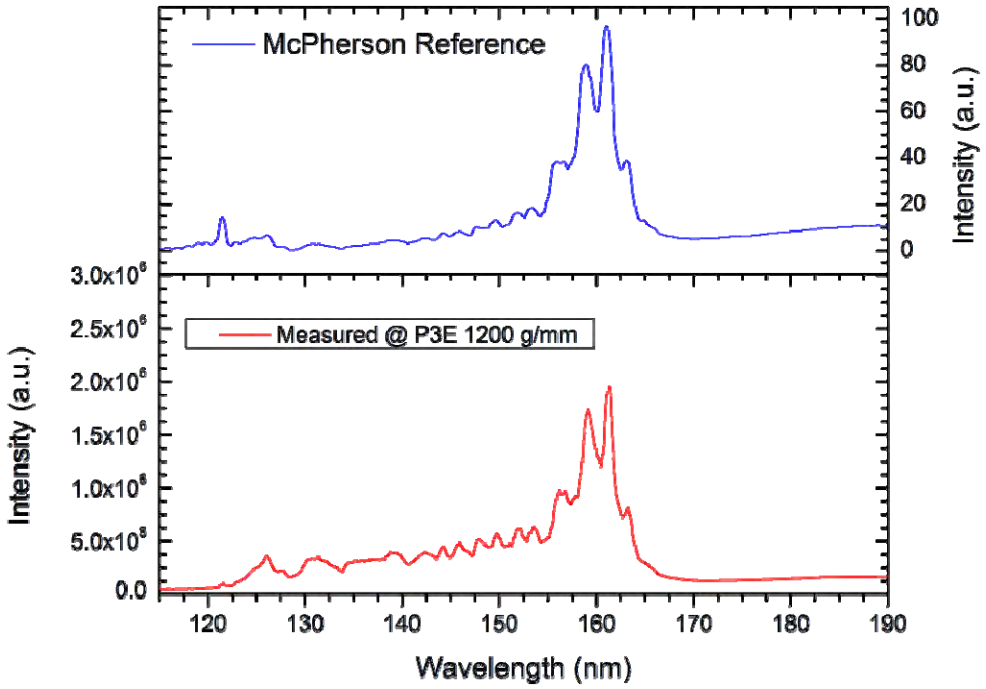

Figure 11: The upper trace is the standard McPherson deuterium spectrum. The lower trace was recorded with the second setup using the mirrors. The ICCD camera used to capture the image has a MgF2 window, thus the drop off at 120 nm.

EXPERIMENTAL RESULTS FROM SETUP TWO

Using the second setup, the spectrum produced by surface breakdown events was recorded for dry air, nitrogen, oxygen, helium, argon, and sulfur hexafluoride. Dry air, nitrogen, and sulfur hexafluoride are commonly used as insulating gases and are, therefore, of interest concerning the effects of VUV on breakdown. Figure 12 depicts the spectrum for dry air using the second system and a comparison with Figure 7 makes it obvious that the features below 180 nm are much easier to evaluate. The other gases produced similar results.

There is an important additional benefit from using the mirrors. It is possible to image the breakdown streamers using the VUV light since there is no chromatic aberration. Such images are shown in Figure 13. For this study, the ICCD was gated for 1 μs, which is long enough to capture the integrated total activity of streamer emission. The ICCD is capable of capturing emission between 115 – 130 nm from triggered discharges in air, N2, and O2 environments, for

an electrode gap distance of roughly 5 mm. Note that the top and bottom pixels of the image correspond to dark areas covered by the electrodes (Figure 13(a)).

Using this method it was possible to observe the entire region from anode to cathode, where the VUV emission spatial profile has been preserved. The integrated spectral profile of the air image is shown on the bottom of Figure 13(b), which matches the previously observed VUV emission spectrum from an air discharge taken with a narrow (50-μm) spectrograph entrance slit. On the right side of each image are representative profiles of nitrogen emission (120.0 and 124.3 nm), oxygen emission (121.7 nm), and probably metal ion lines from the electrodes (126.7 nm).

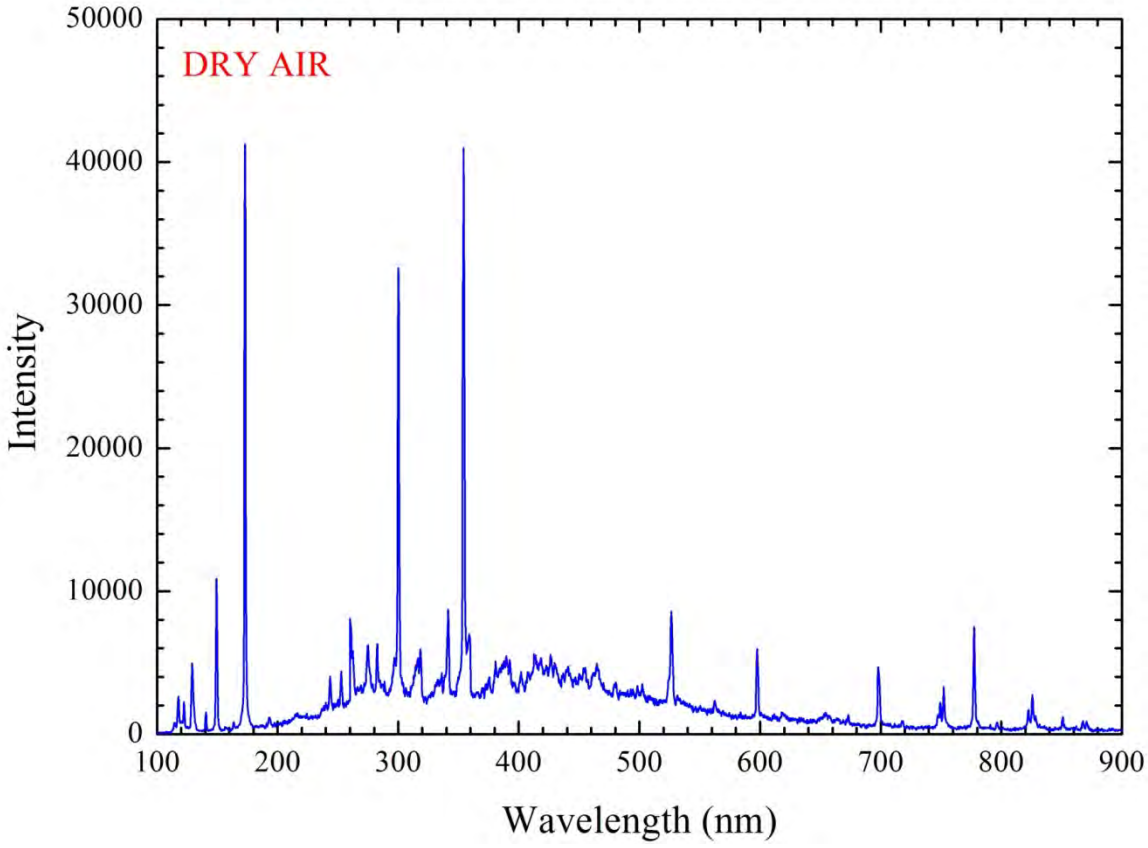

Figure 12: Spectrum of dry air showing the increased efficiency and resolution of the mirror system. This should be compared with Figure 7.

It is observed that the emission from atomic nitrogen N I has the same spatial profile shape at 120.0 and 124.3 nm (only an intensity difference), and this emission is released from excited N I atoms throughout the gap region. However, the observed O I emission at 121.7 nm is strongly released in the area near the cathode only, with limited emission near the anode.

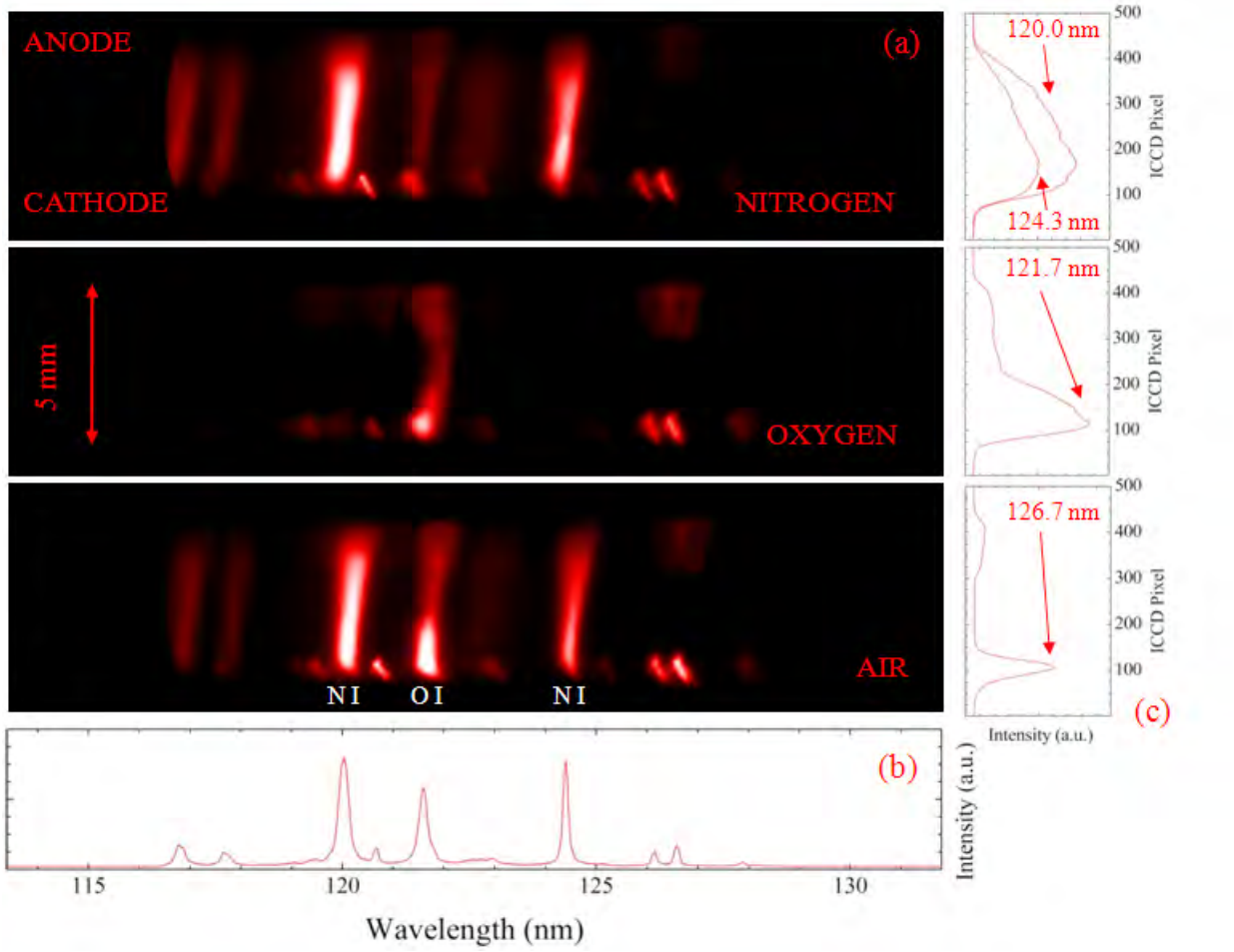

Figure 13. Pseudo-color image of (a) spectrally resolved VUV emission from discharges measured in N_2, O_2, and air environments, where the spatial profile between the anode and cathode has been preserved, (b) integrated emission from breakdown in air, and (c) spatial profiles for NI, OI, and probably metal ion VUV emission during air breakdown.

The observed streamer characteristics in the visible range have been discussed previously [3], where a cross-species process could result in lower breakdown voltages in air compared to either pure N_2 or O_2. Due to the high absorption cross section of oxygen molecules in the VUV range [4], one can speculate that emission from the Birge-Hopfield N_2 excitation band could be easily absorbed by oxygen molecules, causing immediate dissociation. The most intense N I emission (120.0 nm) corresponds to a $2s^22p^2(^3P)3s$ to $2s^22p^3$ transition into the ground state, which is readily excited by electron collision throughout the gap and de-excited by spontaneous emission. As the cathode directed streamer heads (i.e. regions of photoionization) propagate away from the anode and liberated electrons are quickly swept out of the gap, the generation of significant ion space charge is believed to produce an increased electric field amplitude near the cathode. This localized electric field is thought to cause an increase of average electron energy such that the electron energy distribution function is shifted to higher energy values. Hence, a more

effective dissociation of O_2 and excitation of atomic oxygen close to the cathode are expected, likely resulting in the observed strong luminosity of atomic oxygen in this region. It is planned to further uncover the more detailed temporally resolved discharge phenomenology related to VUV emission at atmospheric pressures by utilizing the fast exposure capability of the ICCD camera.

SETUP THREE UNDER CONSTRUCTION

A third setup is under construction and almost complete. This system will be described but no results are presently available. The point to setup three is to eliminate the MgF_2 window on which the surface discharge takes place. This will extend the spectral measurements to shorter wavelengths. It is still desired to make the discharge in atmospheric pressure gas. Therefore, a special chamber has been built to fit on the entrance port of an Acton VM 502 spectrometer. The VM 502 is a nominally 4.0 nm/mm, with 1200 G/mm grating in the first order with a mechanical scanning range in zero order to 546.1 nm. The low wavelength limit is dependent upon light source and detector, but is typically less than 30 nm.

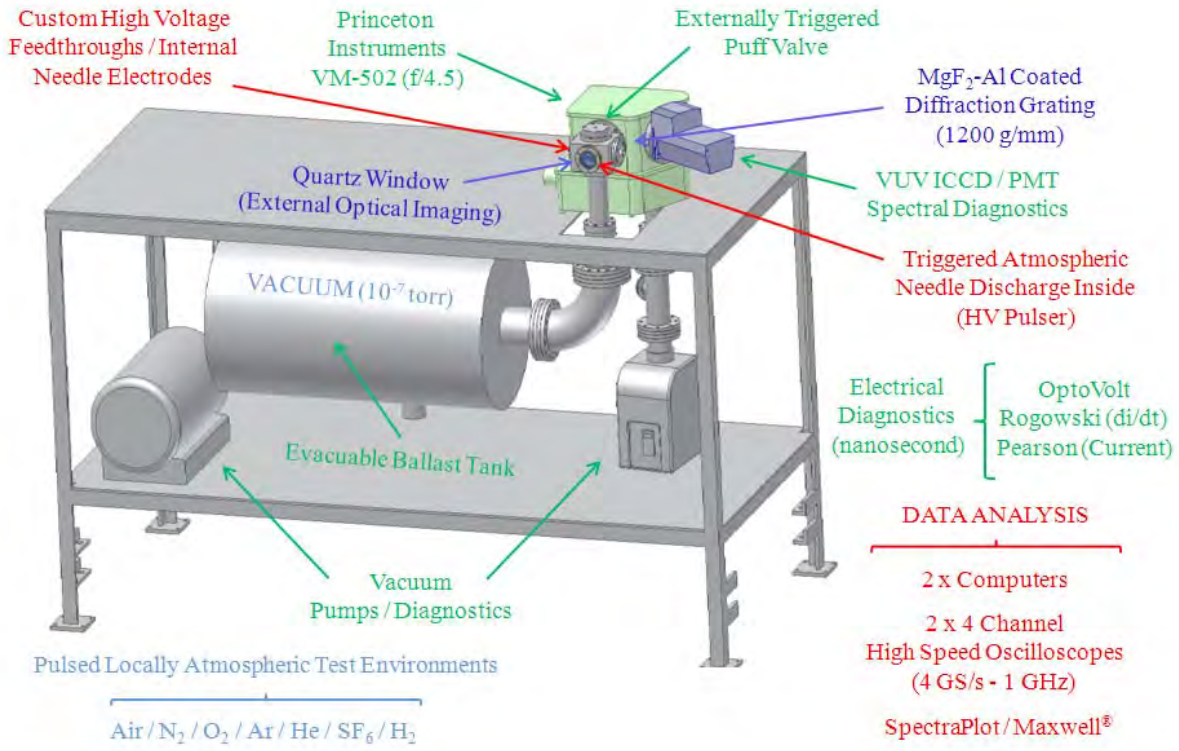

Figure 14. The VM 502 spectrometer with a turbo pumping system and a separate pumping system with a ballast tank for the discharge chamber.

The experimental equipment is shown in Figure 14. The discharge chamber is separated from the spectrometer by a thin plate with a 1 mm wide slit. There are two electrodes between which the high voltage pulser will be attached. On top of the chamber is

a valve which can quickly empty a plenum filled with gas at up to three atmospheres pressure. This "puff valve" opens in 30 microseconds forming a high-pressure region between the electrodes where the discharge occurs. The spectra produced are recorded before the gas can enter the spectrometer so it is possible to observe short wavelength light below 115 nm. The gas expands into a large ballast tank which is evacuated by a high speed turbo pump. The spectrometer is also evacuated by a turbo pump system. The ballast tank keeps the pressure low by expanding the gas and keeps the pumps from being swamped. This new spectrographic system will enable measuring light in a wavelength range capable of directly ionizing molecular oxygen. With the previous setups, light that leads to O_2 dissociation but not direct ionization is captured.

Conclusions

We have presented two experimental setups that allow time resolved imaging and spectroscopy with nanosecond scale temporal resolution. A low jitter, long lifetime, high voltage pulser was constructed and produces repeatable surface flashover events with significant VUV content. PMT and electrical diagnostics confirm that most VUV is emitted during the fast streamer stage before and during initial breakdown. Time resolved spectroscopy using an ICCD shows that limited VUV is emitted during the fully conductive stage of breakdown for many microseconds. Finally, it was shown that nanosecond scale gating of ICCD flashover imaging can be used in conjunction with electrical diagnostics to reconstruct a detailed picture of the initial period of streamer propagation in atmospheric discharges.

The second setup using mirrors instead of an MgF_2 lens significantly improved the efficiency and spectral resolution of the system. It was then possible to image the streamers in VUV light showing that the short wavelength light from atomic oxygen can propagate far enough in atmospheric pressure gas to cause additional ionization thus speeding up the rate of progress of the streamers.

A third setup will allow observation of much shorter wavelengths, perhaps down to 60 nm, because there will be no window between the discharge and the spectrometer. No results from the third setup are available yet.